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Power Flow Analysis Algorithm for Islanded LV Microgrids Including Distributed Generator Units with Droop Control and Virtual Impedance Loop

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***Abstract*—In this paper, an improved power flow analysis algorithm for distributed generation (DG) units controlled with P/Q droop functions and virtual impedances in a low voltage (LV) microgrid is proposed. The proposed analysis provides in contrast to conventional power flow calculation techniques: (i) consideration of virtual impedance parameters and (ii) higher accuracy in reactive power flow calculation. The improved power flow analysis algorithm proposed in this paper is validated by comparing the calculation results with detailed time domain simulation results. Case studies have been carried out by analyzing the effects of control parameter variation in the power flow results obtained by the proposed algorithm.**

I. Introduction

With larger portion of growing electricity demand which is being fed through distributed generation (DG), the concept of microgrid has been introduced as one of the most promising technologies to modernize current power system. Being able to operate in both grid-connected and islanded mode, a microgrid manages and controls distributed energy resources, energy storage systems and loads, most of them are power electronic system interfaced, in a coordinated and hierarchical way [1], [2]. Similar to the bulk power system, the steady-state power flow analysis plays a very important role for the planning and operational stages of the microgrid in terms of systematic analysis, protection, coordination design, network optimization and optimal operation, and so on, which requires more investigation when applied to the microgrids, especially during islanded operation mode.

Recently, in order to address the power flow analysis problem in microgrids and islanded power system, a lot of state-of-the-art work has been done [3]−[6]. Most of the previous work is based on conventional power flow method using conceptual PQ, PV and slack buses. However, it has the limitation that when analyzing an islanded microgrid, there is no such a slack bus which is able to maintain bus voltage and system frequency constants. Instead of assuming one slack bus in the model, in [4]−[6], power flow analysis methods adopting the droop equation constrains in DG units modeling were presented. However, despite of being able to work very well under inductive line impedance, traditional droop control is not applicable in a network with resistive or resistive-inductive mixed line impedances. In these cases, in order to decouple real and reactive power, to increase the stability margin and also to improve the accuracy of reactive power sharing, virtual impedance loops are often adopted in addition to the conventional droop control in power electronics interfaces of each DG unit in LV microgrids [7]− [9],[11].

II. Modeling of the Proposed Power Flow Analysis

When the line impedance is inductive enough (e.g. R/X≈0.31 as mentioned in [10]), either because of long transmission distance or the large output inductor of the output filter, specially here when an LCL filter or transformer are used at the output of the PWM inverter, traditional droop control can achieve proper power sharing among DG units autonomously [1]. In these cases, the DG unit can be modeled as an ideal voltage source whose voltage and frequency are determined by the droop characteristics [4]. However, when the virtual impedance control strategy is adopted in power electronics systems inside a network with highly resistive line impedance, the output voltage characteristics of the DG units are no longer purely determined by droop equations.

In [7]−[9], the principle of the virtual impedance control strategy is used as illustrated in Fig.1. As it can be seen, for a droop controlled DG bus, without the virtual impedance Z_v, the voltage at the terminals of the generator (V_G) is equal the voltage reference provided by the droop control (V_{droop}), so that the frequency and the voltage amplitude can be defined as

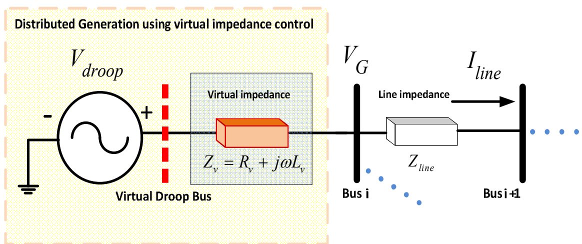

Figure 1. Virtual impedance control concept

follows:

$$f^* = f_{0i} - K_{Pi}P_{Gi} \quad (1)$$

$$|V_{Gi}| = |V_{G0i}| - K_{Qi}Q_{Gi} \quad (2)$$

being f_{0i}, K_Pi, P_{Gi},V_{G0i}, K_{Qi}, Q_{Gi} the nominal frequency, proportional frequency droop parameter, real power generation, nominal voltage, proportional voltage amplitude droop parameter, and reactive power at generator i, respectively.

Taking into account that the frequency is a global variable for all the DG buses throughout the microgrid, from (2) we can obtain:

$$f_{0i} - K_{Pi}P_{Gi} = f_{0g} - K_{Pg}P_{Gg} \quad (3)$$

where i=1,…, g-1, being g the number of the buses.

However, with a none-zero value of Z_v, the matrix of DG buses voltage V_G takes the form:

$$\begin{aligned} V_G &= V_{droop} - I_{Gline}Z_v \\ &= V_{droop} - (Y_{Gbus}V_G)Z_v \end{aligned} \quad (4)$$

where the V_{droop} is the voltage of the virtual droop bus, I_{Gline} the injection current in the generation bus, Y_{Gbus} the admittance of the network directed connected to the generation buses, Z_v the virtual impedance of the controller and V_G the voltage in generation bus.

The network equations that all buses should obey are given by:

$$P_i = V_i \sum V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \quad (5)$$

$$Q_i = V_i \sum V_j (G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}) \quad (6)$$

where θ_{ij} , G_{ij} and B_{ij} are the bus admittance angle, the conductance and the susceptance, respectively.

The mathematic model of the proposed power flow analysis can be obtained as follows:

$$\begin{cases} f_{0i} - f_{0g} - K_{Pi}P_{Gi} + K_{Pg}P_{Gg} = 0 & (7) \\ |V_{G0i}| - |V_{Gi}| - K_{Qi}Q_{Gi} = 0 & (8) \\ P_{Gi} - P_{Di} - P_i = 0 & (9) \\ Q_{Gi} - Q_{Di} - Q_i = 0 & (10) \\ V_G - V_{droop} + (Y_{Gbus}V_G)Z_v = 0 & (11) \end{cases}$$

III. ALGORITHM VALIDATION

The validation of the proposed power flow analysis algorithm is verified by comparing the steady-state results in time domain simulation of the detailed model in SimPowerSystems. The tested six-bus microgrid system with R/X≈7.7 in typical low voltage lines [10] is shown in Fig. 2. All the DG units are power electronics interfaced and controlled by the droop method plus a virtual impedance loop. The system parameters of the 6-bus system are shown in Table I. In Table II, good agreement between the simulation results and calculated power flow analysis results, with bus voltage magnitude deviation less than 0.16% and bus voltage angle deviation less than 0.0021 degree, shows the applicability of the proposed method for islanded LV microgrids. As it can be seen in Fig. 3, compared with the traditional algorithm which

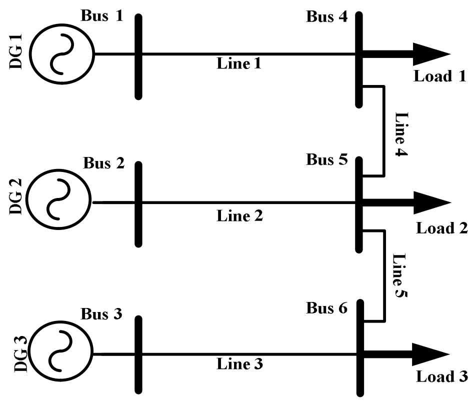

Figure 2. Single line diagram of the six-bus microgrid

TABLE I CONTROL PARAMETERS OF DG UNITS IN 6-BUS STSTEM

Parameters	Symbol	Value	Units
Power stage			
Line resistor	$R_{line\_}$	0.15	Ω
Line inductor	$L_{line\_}$	0.000062	H
LC filter inductor	L_f	1.8	mH
LC filter capacitor	C_f	27	μF
Control parameters			
Proportional frequency droop for DG1	K_{P1}	0.001	rad/(W · s)
Proportional amplitude droop for DG1	K_{Q1}	0.02	V/Var
Proportional frequency droop for DG2	K_{P2}	0.0005	rad/(W · s)
Proportional amplitude droop for DG2	K_{Q2}	0.01	V/Var
Proportional frequency droop for DG3	K_{P3}	0.004	rad/(W · s)
Proportional amplitude droop for DG3	K_{Q3}	0.02	V/Var
Virtual resistor	R_{v_n}	0.1	Ω
Virtual inductor	L_{v_n}	0.004	H
Load parameters			
bus number	R_{load}	L_{load}	
4	100Ω	0	
5	100Ω	0	
6	100Ω	0.25136H	

TABLE II. VALIDATION RESULTS OF THE SIX-BUS MICROGRID

	SimPowerSystem results		Power Flow Results	
Node	**Mag.(p.u.)**	**Ang.(degree)**	**Mag.(p.u.)**	**Ang.(degree)**
1	0.976127	0	0.977708	0
2	0.977612	0.015905	0.979174	0.017189
3	0.975439	0.050155	0.977047	0.051568
4	0.974967	0.004779	0.976571	0.00573
5	0.97531	0.020829	0.976914	0.022919
6	0.974856	0.053096	0.976477	0.051568

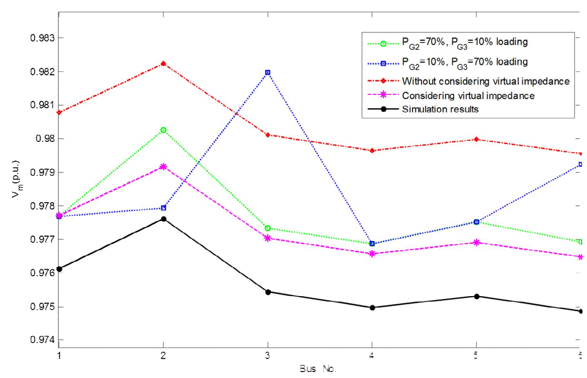

Figure 3. Comparison of voltage profiles of the six-bus test system using different methods

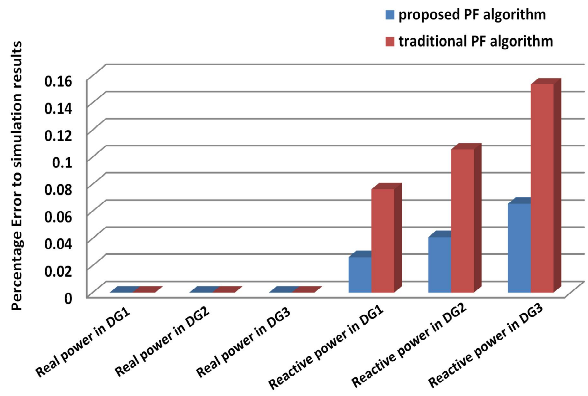

Figure 4. Comparison of Percentage Error of DG Power with and without considering virtual impedance

sets one slack bus and the algorithm without considering virtual impedances, the results obtained from proposed algorithm are much closer to the time-domain simulation results. As it is shown in Fig. 4, the percentage error (defined as |calculation result-simulation result|/simulation result) of reactive power generated by DGs, is reduced notably by using the proposed method, and thus indicates the superiority of the proposed method when analyzing LV microgrids.

IV. CASE STUDIES

In this Section, a 38-bus system has been chosen as the studied system to further test the effectiveness of the proposed algorithm and to observe the effects of control variables in DG units on the power flow. The 38-bus system used is the one in [12] with a slight modification of the generation location to distribute the DG units more evenly. The five droop controlled DG units located in buses 34, 35, 36, 37 and 38 are connected to buses 8, 29, 12, 22 and 25 respectively, and the feeder parameters and load power data remain the same with that in [12]. Fig. 5 shows the topology of the 38-bus system. Table III shows the static droop coefficients, nominal settings, and virtual impedance parameters of the DG units. Based on this

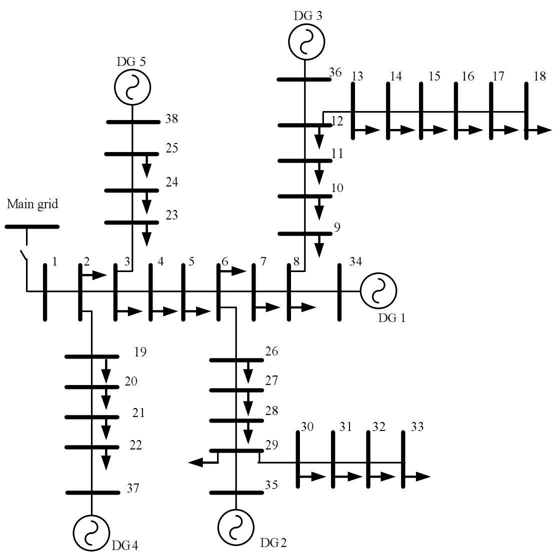

Figure 5. The topology of 38-bus system

system, several case studies have been carried out to study how the control of the DG units will affect the power flow of the system.

TABLE III. CONTROL PARAMETERS OF DG UNITS IN 38-BUS STSTEM

DG #	Bus #	K_P (p.u.)	K_Q (p.u.)	f_0 (p.u.)	V_{G0} (p.u.)	R_v (p.u.)	X_v (p.u.)
1	34	0.004504	0.036239	0.977708	1.03	0.0032	0.0297
2	35	0.001501	0.072457	0.979174	1.03	0.0032	0.0297
3	36	0.002304	0.021739	0.977047	1.03	0.0032	0.0297
4	37	0.002252	0.108696	0.976571	1.03	0.0032	0.0297
5	38	0.000751	0.021739	0.976914	1.03	0.0032	0.0297

A. *Case 1: Effects of Droop Gain*

In contrast to the traditional power flow algorithm, the algorithm considering droop control has the benefit of analyzing the power sharing according to the droop parameters, which is unachievable in conventional methods. However, without considering virtual impedance used commonly in the DG units in the LV network, as discussed in previous Sections, the power sharing is not exactly according to the droop parameters, especially for the reactive power flow. The proposed algorithm can be used to obtain a more accurate power flow distribution before commitment based the control variables in DG units.

In order to evaluate how K_P may affect the real power sharing, K_P parameters in bus 34 and 38 are swapped in the comparison simulation. The variation in the results of real power generation in these two scenarios is illustrated in Fig. 6. As can be seen, the real power in bus 34 and 38 are almost reversed, while other buses remain quite the same. This Fig. also shows that the real power are shared according to the proportion of K_P between each DG bus. Note that the all the other parameters which might affect reactive power are kept the same in the test system, e.g. nominal frequency, virtual impedance, etc. As can be seen in Fig. 7, the change of the K_Q changes the reactive power distribution among DG units. However, unlike that for the real power, the sharing is not precisely reversed and reactive power in other buses is also influenced. It emphasizes again that the reactive power of DG units is not proportional to the K_Q [1], and an accurate power flow analysis is needed in the designing the K_Q for each DG unit.

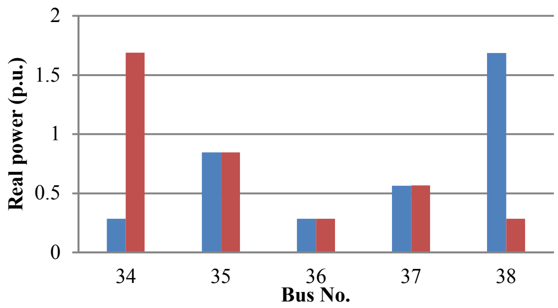

Figure 6. Effects of K_P on generated real power in DG buses

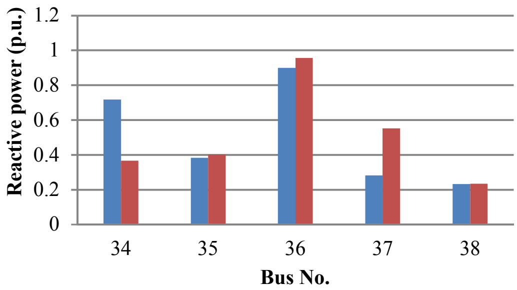

Figure 7. Effects of K_Q on generated reacitve power in DG buses

B. *Case 2: Effects of Virtual Impedance*

As newly introduced parameters in the controller of DG units, virtual impedance might also influence the power flow of the system. To view their effects on system voltage profile and generation power, the value of virtual reactance in bus 35 is increased from 0.0297 p.u. to 0.0495 p.u. The results of increasing the virtual reactance in bus 34 to 0.0495 p.u. are also showed in Fig. 8. The results show that, with the increase of the virtual reactance, the voltage profile of the system will be levelled down as in (a), which is also coincident with (4). The reactive power in corresponding bus will be decreased with the increasing of the virtual reactance as in (c), which also means that this value can be used to regulation the reactive power in the system. For the generated real power in DG units, the changing of virtual reactance almost has no effects as shown in (b). Since the control cycle is very short for droop control and virtual impedance, these parameters can be control for the fast power flow regulation event, e.g. to reduce the virtual reactance during fault ride through [7].

Similar result of changing the virtual resistance in the controller obtains the similar conclusion. With limitation of the space, the result is not shown here. It should be noticed that virtual resistance might not be a proper control variable to regulate the power flow, as its main purpose is to increase the system damping and theoretically the smaller the total output resistance for the DG unit the better the decoupling of real and reactive power for the control [7].

C. *Case 3: Effects of Nominal Values*

Not only the droop gains have influences on the power flow, the nominal value in the droop ef equations (1) and (2) also effect the power distribution. To observe the effects of nominal frequency, the nominal frequency in only one bus is changed. Fig. 9 Shows the generation real power result when changing the nominal frequency in bus 34 form 1 p.u. to 1.004 p.u., and when nominal frequency in bus 36 the changing from 1 p.u. to 1.002 p.u. As can be seen in this system, increasing

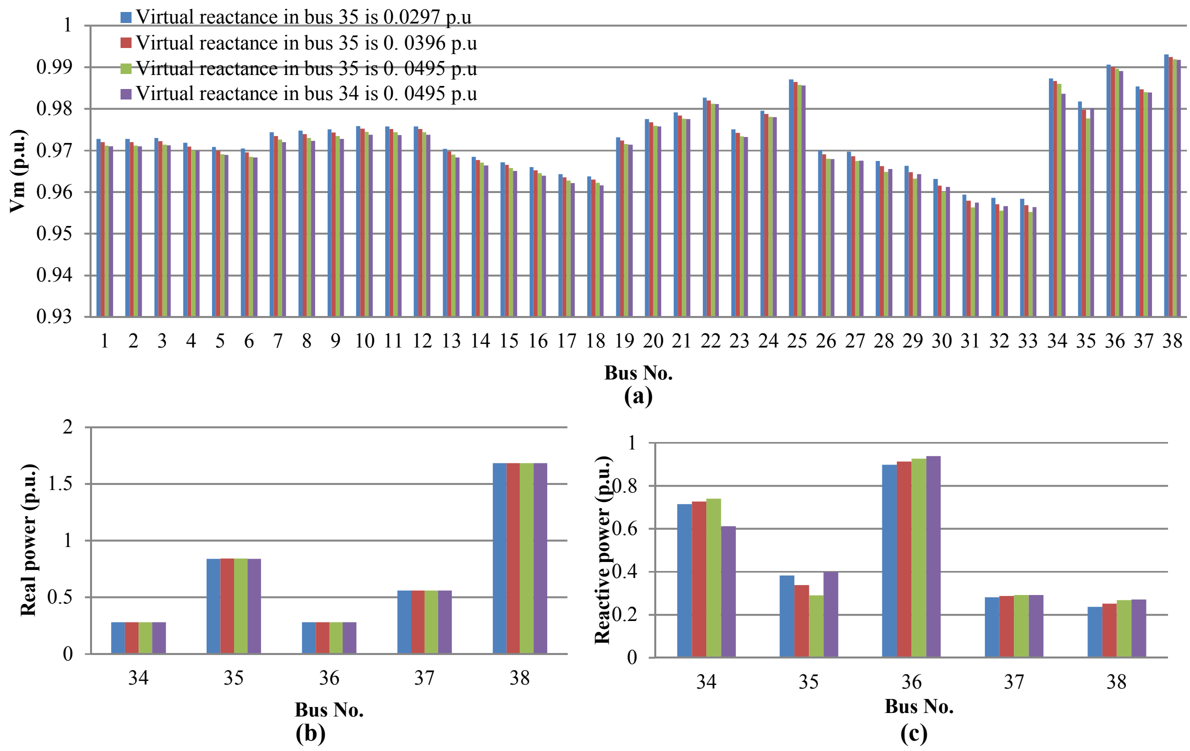

Figure 8. Effects of virtual reactance on power flow

the nominal value of the DG unit in bus 34 and 36, the real power accordingly is increased, and static frequency of the system is 0.9987, 0.9989, 0.9991 and 1.0009 for these scenarios respectively. It shows that increasing the nominal frequency, the corresponding bus might increase the real power to level the system frequency. Since the frequency droop gain also determines the real power sharing as a control variable, this might not be a general conclusion, but for most of the cases, this can be used to regulate the system frequency. To see the influence of the nominal voltage, the nominal value of the all the DG units are changed from 1.01 p.u. to 1.05 p.u., and the voltage profile is shown in the Fig. 10. It can be seen that increasing the nominal value of all the generation, the voltage profile will be levelled, so this can be controlled to regulate the system voltage, as in the secondary control in [1].

It is worthy noticing that regulation of nominal value should not be active for all the change of the frequency and voltage in order to avoid the confliction with the primary control which regulates the droop gains and virtual impedance. Only when the frequency and voltage deviation

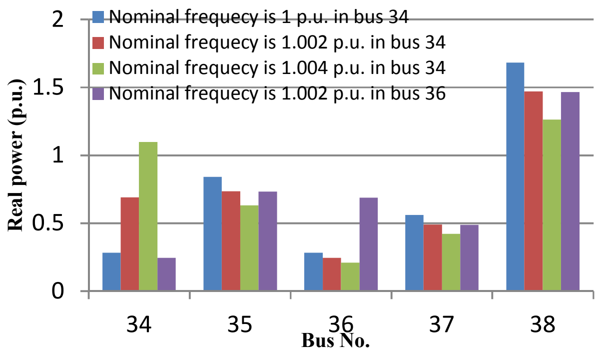

Figure 9. Effects of nominal frequency on generation real power

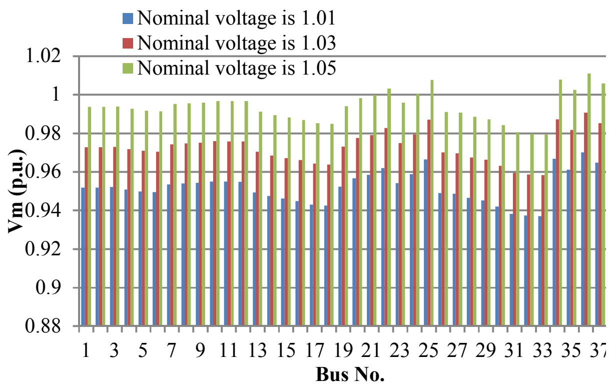

Figure 10. Effects of nominal Voltage on voltage profile

exceeds the allowable limitation, these parameters should be regulated to maintain the power quality for the system.

V. Conclusion

An improved power flow analysis algorithm considering the virtual impedance control is proposed for LV microgrids, where resistive line impedance necessitates the use of virtual impedance. The implemented power flow analysis is verified by comparing the calculation results with detailed time domain simulation results. Improved accuracy is achieved using the proposed power flow algorithm, especially for the reactive power of generation buses. Case studies in 38-bus system are given to discuss the effects of frequency and voltage droop gain, virtual impedance, nominal frequency and nominal voltage on the power flow, which shows the necessity of an accurate power flow analysis to evaluate the influence of them on the system power flow.

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